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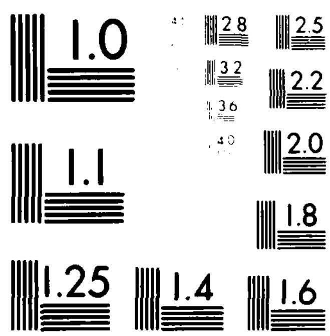

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TECHNICAL REPORT ARCCB-TR-86021

UNLOADING-COMPLIANCE AND LOAD-DROP ANALYSIS OF J_{Ic} TESTS OF IRRADIATED 348 STAINLESS STEEL

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JUNE 1986

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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Procedures for determining J integral fracture toughness were applied to load versus load-line displacement data from a series of three-point bend specimens of irradiated 348 stainless steel tested at 23°C and 427°C. ASTM Method E813 for J_{Ic} was emphasized, using both unloading-compliance and load-drop measures of crack growth.

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20. ABSTRACT (CONT'D)

An effective modulus procedure was included in the unloading-compliance method using recently published load-line displacement results. Two procedures were used for calculating J_{Ic} from the J versus unloading-compliance crack growth plots: the linear fit procedure from E813 and a power law fit with a 0.2 mm offset value of J_{Ic}.

Based on the results of these various procedures, conclusions were reached regarding the most consistent measures of fracture toughness from these data. Suggestions were given regarding the use of effective modulus with unloading-compliance measurement of crack growth and the limitations of the load-drop method for measuring crack growth.

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INTRODUCTION AND OBJECTIVE

Fracture toughness testing of ductile materials is a complex procedure in the best of circumstances. For difficult testing conditions the complexity is compounded. One such set of conditions is J_{Ic} testing of irradiated structural materials from nuclear power generating equipment (ref 1). Materials which have been irradiated are often hazaradous to test using the usual methods, so they must be tested remotely in a closed hot cell. Remote J_{Ic} tests present special problems such as the limitations imposed on specimen displacement measurement, a critical part of the J_{Ic} test procedure. Test results of irradiated 348 stainless steel are described here and analyzed using two methods. One, which has become quite standard in J_{Ic} testing, is the unloading-compliance method (ref 2). The other is the more recently proposed load-drop method (ref 3). Both methods were applied to the same load versus load-line displacement data, P versus δ, from a series of three-point bend specimens of irradiated 348 stainless steel tested at 23°C and 427°C, using ASTM Method E813 procedures whenever possible.

The objective here was to evaluate the J_{Ic} test procedure under nonideal, remote testing conditions, using two methods of crack growth measurement well-

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[1] F. M. Haggag, W. L. Server, W. G. Reuter, and J. M. Beeston, "Effects of Irradiation Fluence and Creep on Fracture Toughness on 347/348 Stainless Steel," Effects of Radiation on Materials, ASTM STP 870, ASTM, 1985, pp. 548-562.

[2] G. A. Clark, W. R. Andrews, P. C. Paris, and D. W. Schmidt, "Single Specimen Tests for J_{Ic} Determination," Mechanics of Crack Growth, ASTM STP 590, ASTM, 1976, pp. 27-42.

[3] J. A. Kapp and J. H. Underwood, "Single Specimen J-Based Fracture Toughness Test for High-Strength Steels," Fracture Mechanics: Fourteenth Symposium - Vol. II: Testing and Applications, ASTM STP 791, (J. C. Lewis and G. Sines, eds.), ASTM, 1983, pp. II-402 - II-414.

suited for remote testing, the unloading-compliance and load-drop methods. Comparison of the values of fracture toughness with other results and the important relation of toughness to the function of power generation equipment are considered elsewhere (refs 1,4). In this work we describe fracture toughness test procedures which proved useful in the testing of irradiated materials and which may be helpful in other difficult testing conditions and in J_{Ic} testing in general.

TEST PROCEDURES

The specimens described here were fabricated from 348 stainless steel sheet, irradiated in an experimental reactor at 427°C to about the same fluence level, and tested in bending at 427°C or 23°C in a hot cell. See Table I and Figure 1 for the key test conditions and arrangements. Specimen dimensions were depth, W = 10.0 mm; gross thickness, B = 5.1 mm; span, S = 40.6 mm; and notch width, η = 4.4 mm. Note in Figure 1 that the displacement gage made contact with the specimen at the edges formed between the notch and the lower specimen surface and that the geometry of this contact was taken into account in calculating the corrected load-line displacement, δ. This calculation of δ does not account for large crack-opening-displacements and specimen rotations, thus it may not be adequate for J-R curve determination,

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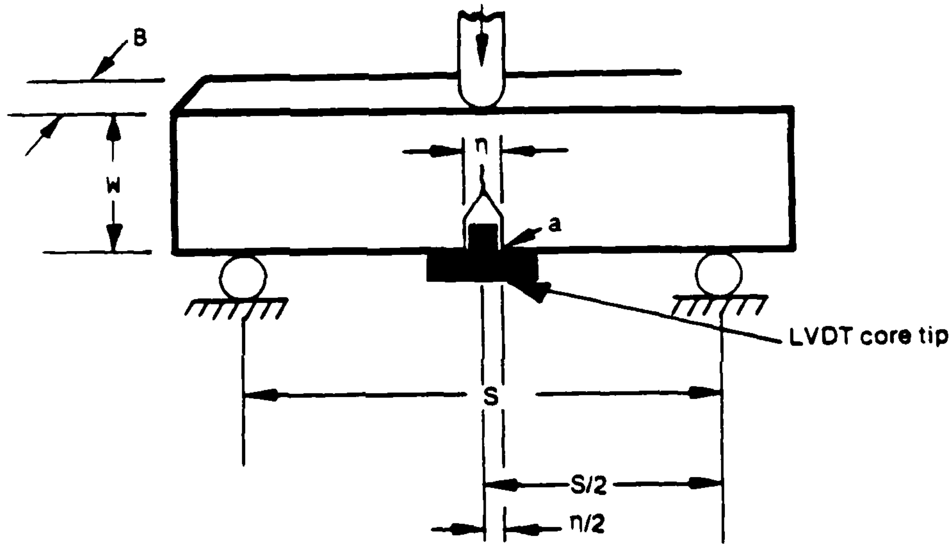
[1]F. M. Haggag, W. L. Server, W. G. Reuter, and J. M. Beeston, "Effects of Irradiation Fluence and Creep on Fracture Toughness on 347/348 Stainless Steel," Effects of Radiation on Materials, ASTM STP 870, ASTM, 1985, pp. 548-562.

[4]F. M. Haggag and A. K. Richardson, "Precracking and Computerized Single-Specimen J_{Ic} Determination for Irradiated Three-Point Bend Specimens," presented at Eighteenth National Symposium on Fracture Mechanics, Boulder, CO, June 1985.

for example. Table I shows the specimen yield strengths in the temperature and irradiation conditions of the tests. The effective yield strength σ_Y, is the mean value of yield and ultimate strengths, as defined in Method E813. The initial crack lengths and the side-groove conditions are given. Specimens 40A and 40B, taken from the same piece as specimen 40, were tested with ten percent side grooves in each side.



δ = Load-line displacement
δ' = Measured displacement at point a

$$\frac{\delta}{\delta'} = \frac{S/2}{S/2-n/2}$$

Figure 1. Test arrangement and calculation of load-line displacement for bend tests performed remotely within a hot cell.

TABLE I. TEST CONDITIONS FOR IRRADIATED 348 STAINLESS STEEL BEND SPECIMENS

Specimen Number	Test Temperature °C	Irradiation Fluence n/cm^2	Yield Strength σ_{ys} MPa	Effective Yield Strength σ_Y MPa	Initial Crack Length a_o/W	Side Groove B_{net}/B
40	427	3.4×10^{22}	747	767	0.49	1.0
47	427	3.4×10^{22}	747	767	0.50	1.0
40A	427	3.4×10^{22}	747	767	0.58	0.8
40B	427	3.4×10^{22}	747	767	0.47	0.8
97	23	2.4×10^{22}	1036	1114	0.48	1.0

Load versus load-line displacement plots were obtained for each specimen, including several partial unloadings to about 86 percent of the current load at the time of the unloading. Two aspects of the test apparatus and procedure were closely controlled in order to improve the accuracy of the unloading. The displacement transducer core was spring loaded so as to minimize the mechanical hysteresis effect in the measurement of an unloading displacement. Also, the load was allowed to relax at constant displacement for ten seconds before each unloading. Two plots of several unloadings are shown in Figure 2 for specimens with nearly the same test conditions except for test temperature. The important differences in load-displacement and associated fracture toughness behavior are discussed elsewhere (refs 1,5). The unloading portions of the traces were plotted separately with expanded scales and evaluated for selection of the more linear portions. The top 30-45 percent and the bottom 7-20 percent of the data were eliminated from a linear regression calculation of the unloading slope. This relatively large amount of data elimination was necessary to obtain an accurate slope for this material and for the type of displacement measurement which was dictated by the closed hot cell. The final crack length for each specimen was marked by heat tinting. The unloading slopes were used to calculate crack growth using the procedures in the following discussion of test data analysis.

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[1] F. M. Haggag, W. L. Server, W. G. Reuter, and J. M. Beeston, "Effects of Irradiation Fluence and Creep on Fracture Toughness on 347/348 Stainless Steel," Effects of Radiation on Materials, ASTM STP 870, ASTM, 1985, pp. 548-562.

[5] F. M. Haggag and A. K. Richardson, "Fracture Toughness and Stress Relief Response of Irradiated 347/348 Stainless Steel," PR-T-84-018, EG&G Idaho, Inc., October 1984.

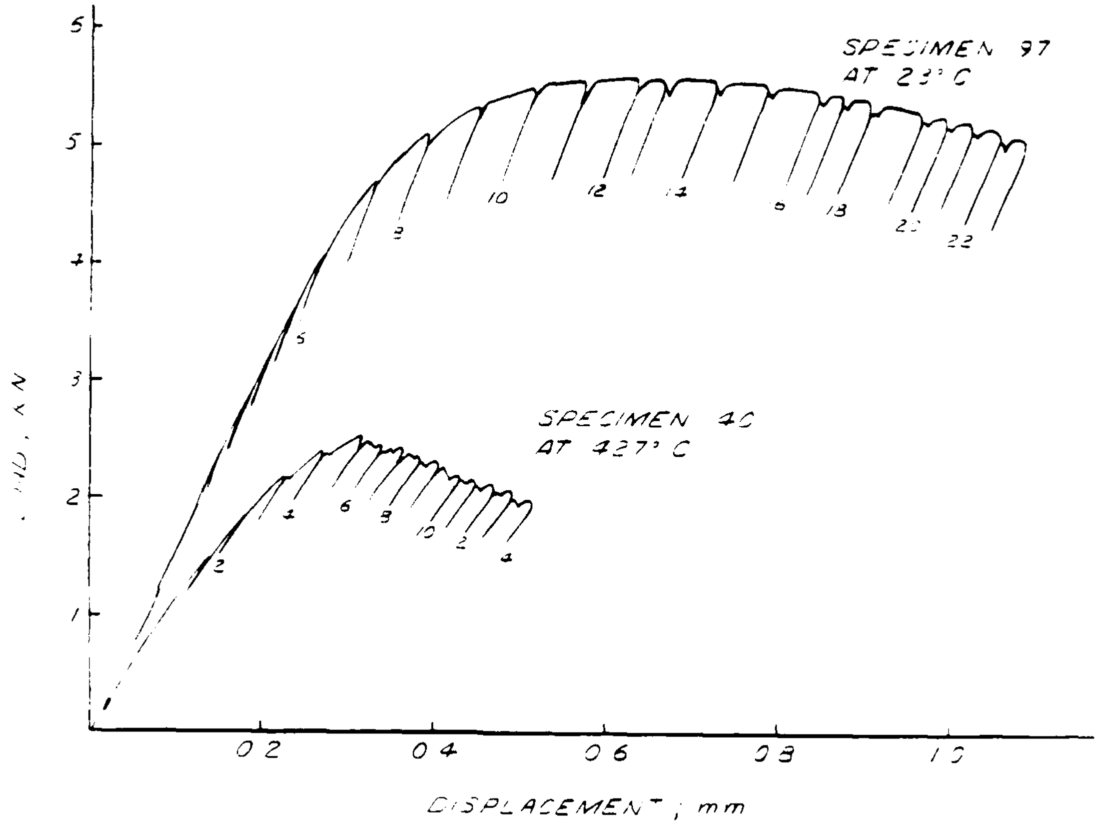

Figure 2. Load versus load-line displacement plots from irradiated 348 stainless steel bend specimens.

DATA ANALYSIS

Unloading-Compliance and Effective Modulus

When J versus Δa data are plotted using Δa obtained directly from an unloading-compliance method, it is often clear that some further analysis is required before J_{Ic} can be determined. This was true for the tests here. Figure 3(a) shows J versus Δa data with J calculated as suggested in Method E813 and Δa calculated from unloading compliance using an elastic modulus typical of the irradiated material at 427°C. Note that the first unloading predicts a negative crack growth and subsequent unloadings result in Δa values which appear to be shifted to the right by about 0.16 mm. This type of zero shift is not uncommon when unloading compliance is used without some sort of

calibration process. For the tests here, the shift may be due to unavoidable test variations and extraneous system and specimen compliance, as well as uncertainties in the value of elastic modulus. All of these problems are compounded by the testing of an irradiated material.

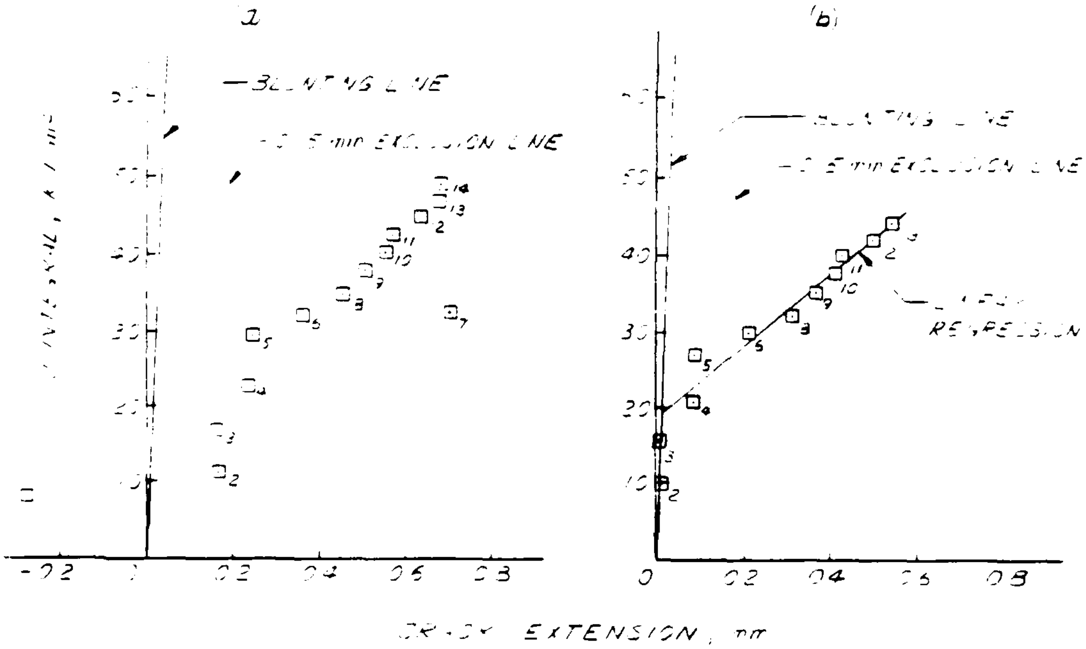

Figure 3. J versus Δa plots for specimen 40.
(a) Using typical modulus, 166 GPa.
(b) Using effective modulus from unloading #2, 156 GPa.

An effective modulus procedure was used to calibrate the unloading-compliance method and resulted in the plot of Figure 3(b). Table II outlines the procedure. The slope from an unloading at about 80 percent of the maximum load is used with the typical modulus to calculate $EB\delta/P$. An unloading at about 80 percent of maximum load is used for this material because it is low

TABLE II. PROCEDURE FOR CALCULATING EFFECTIVE MODULUS, E*, FOR SPECIMEN 40

Using Typical Modulus: E = 166 GPa		Calculate Effective Modulus, E*				
From Calibration Unloading: #2 $EB\delta/P$	Indicated Crack a/W	Actual Crack a_o/W	Δa Due to Blunting $\frac{\Delta a_b}{W} = \frac{J}{2\sigma_y W}$	Total Crack a_t/W	Effective Compliance $EB\delta/P)^*$	$E^* = E \frac{(EB\delta/P)^*}{(EB\delta/P)}$
56.9	0.504	0.487	0.001	0.488	53.4	156 GPa

enough on the curve so that crack growth has not yet begun and, at the same time, it is high enough on the curve that the low-load system irregularities have long since passed. Furthermore, it is advisable to calibrate the unloading-compliance method at a load as close as possible to the loads at which it will be used. The value of $EB\delta/P$ determined as described above from the calibration unloading was used to obtain an indicated value of initial crack length, $a/W = 0.504$, in this case, from the following compliance expressions (ref 6):

$$\frac{EB\delta}{P}\left(\frac{1-a/W}{S/W}\right)^2 = 1.193 - 1.980\ a/W + 4.478\ (a/W)^2$$

$$-4.443\ (a/W)^3 + 1.739\ (a/W)^4 \qquad (1)$$

$$\gamma = \frac{1}{1 + (EB\delta/P)^{1/2}} \qquad (2)$$

$$a/W = f(\gamma) = 1 - 3.82\ \gamma + 7.85\ \gamma^2 - 384\ \gamma^3 + 3852\ \gamma^4 - 12050\ \gamma^5 \qquad (3)$$

Equation (1) is believed to be accurate within one percent for $0 \leq a/W \leq 1.0$ and $S/W = 4$, and Eqs. (2) and (3) are believed to be accurate within two percent for $0.4 \leq a/W \leq 1.0$ and $S/W = 4$. Table III gives values from Eq. (1) for quick reference. The above compliance expressions are used because recent results (refs 6,7) have shown that they are more accurate than the compliance data in Method E813. For example, the value of $EB\delta/P$ for $a/W = 0.5$ from the expressions here is 11.9 percent higher than the value from Method E813. We

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[6] J. H. Underwood, J. A. Kapp, and F. I. Baratta, "More on Compliance of the Three-Point Bend Specimen," International Journal of Fracture, Vol. 28, 1985, pp. R41-R45.

[7] F. M. Haggag and J. H. Underwood, "Compliance of Three-Point Bend Specimen at Load Line," International Journal of Fracture, Vol. 26, 1984, pp. R63-R65.

TABLE III. VALUES OF DIMENSIONLESS LOAD-LINE DISPLACEMENT, $EB\delta/P$, VERSUS CRACK LENGTH, a/W, FROM WIDE RANGE EXPRESSION (REF 6), EQUATION (1).

a/W	EBδ/P	a/W	EBδ/P	a/W	EBδ/P	a/W	EBδ/P	a/W	EBδ/P
0.400	39.006	0.500	56.052	0.600	88.277	0.700	159.07	0.800	364.95
0.405	39.646	0.505	57.202	0.605	90.576	0.705	164.64	0.805	384.37
0.410	40.305	0.510	58.389	0.610	92.967	0.710	170.51	0.810	405.36
0.415	40.981	0.515	59.615	0.615	95.453	0.715	176.69	0.815	428.10
0.420	41.677	0.520	60.880	0.620	98.040	0.720	183.22	0.820	452.79
0.425	42.393	0.525	62.188	0.625	100.73	0.725	190.11	0.825	479.66
0.430	43.129	0.530	63.538	0.630	103.53	0.730	197.39	0.830	508.98
0.435	43.886	0.535	64.934	0.635	106.46	0.735	205.09	0.835	541.03
0.440	44.666	0.540	66.377	0.640	109.51	0.740	213.25	0.840	576.18
0.445	45.468	0.545	67.870	0.645	112.69	0.745	221.90	0.845	614.83
0.450	46.293	0.550	69.414	0.650	116.01	0.750	231.09	0.850	657.46
0.455	47.144	0.555	71.012	0.655	119.48	0.755	240.85	0.855	704.65
0.460	48.019	0.560	72.666	0.660	123.10	0.760	251.24	0.860	757.04
0.465	48.920	0.565	74.379	0.665	126.89	0.765	262.31	0.865	815.44
0.470	49.849	0.570	76.154	0.670	130.86	0.770	274.12	0.870	880.79
0.475	50.806	0.575	77.994	0.675	135.02	0.775	286.75	0.875	954.24
0.480	51.792	0.580	79.901	0.680	139.37	0.780	300.25	0.880	1037.1
0.485	52.808	0.585	81.879	0.685	143.94	0.785	314.72	0.885	1131.2
0.490	53.856	0.590	83.932	0.690	148.74	0.790	330.26	0.890	1238.6
0.495	54.937	0.595	36.063	0.695	153.78	0.795	346.96	0.895	1361.9

[6] J. H. Underwood, J. A. Kapp, and F. I. Baratta, "More on Compliance of the Three-Point Bend Specimen," International Journal of Fracture, Vol. 28, 1985, pp. R41-R45.

believe the difference is due to the omission of the no-crack shear displacement in the E813 data and the inaccuracy of the displacement expression which accounts for the presence of the crack in the E813 data.

Referring again to the calculation of effective modulus, as outlined in Table II, a total initial crack length, a_t/W, is calculated as the sum of the actual initial crack length from the heat tinted fracture surface and an additional amount due to blunting, $\Delta a_b/W$. The value of effective compliance, $(EB\delta/P)^*$, corresponding to a_t/W, is determined from Table III and used as shown to calculate effective modulus, 156 GPa. This value of effective modulus is used to calculate Δa from all the test unloadings, resulting in the plot of Figure 3(b). Linear regression was used to fit a line to points from unloadings 6 and 8 through 13; unloading 7 was omitted due to excessive nonlinearity, noticeable even in the unexpanded plots of Figure 2; unloading 14 was omitted because the automated evaluation of this last unloading may have been interrupted. Linear regression and power law regression fits were performed on the unloading-compliance data for all specimens. Two examples are shown in Figures 4 and 5. The power law regression was performed as follows:

$$\ell n\ J = \ell n\ A + n\ \ell n\ \Delta a \tag{4}$$

where J was obtained from the crack-growth-corrected procedure of Method E813. Linear regression of ℓn J on ℓn Δa was used to obtain an expression in the form

$$J = A\Delta a^n \tag{5}$$

The critical value of J is the intersection of the power law curve with a 0.2 mm offset line parallel to the blunting line, as shown in Figures 4 and 5.

This critical value, being considered as a revised J_{Ic} test procedure, will be compared with the current Method E813 J_{Ic} value obtained from the intersection of the linear curve with the blunting line.

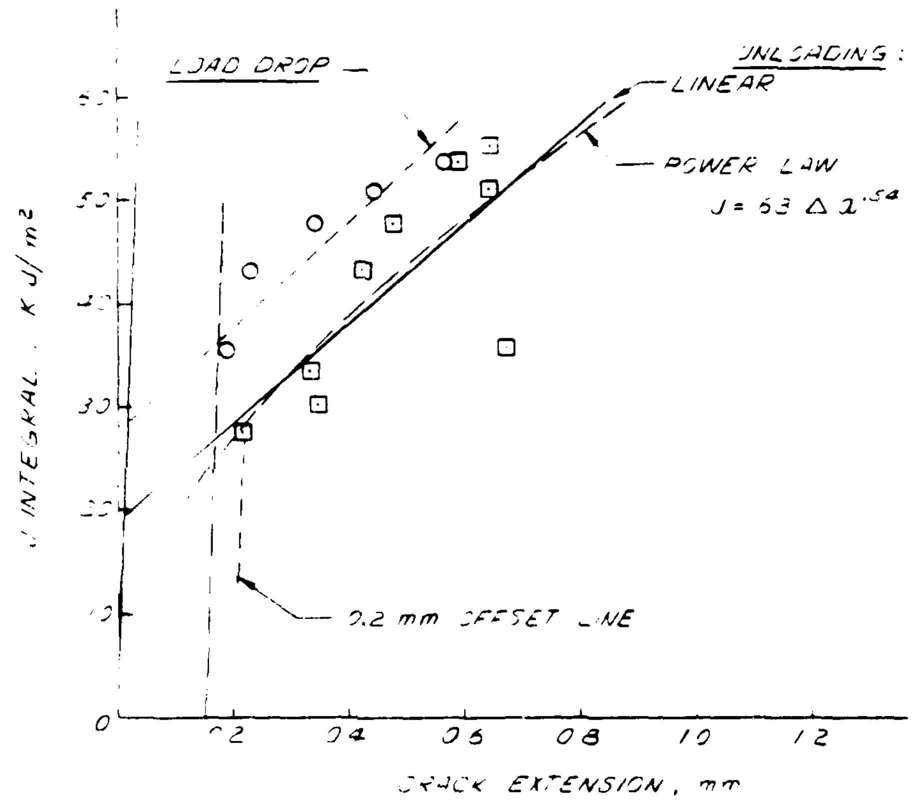

Figure 4. J versus Δa plots for specimen 47, using unloading-compliance and load-drop measurement of Δa.

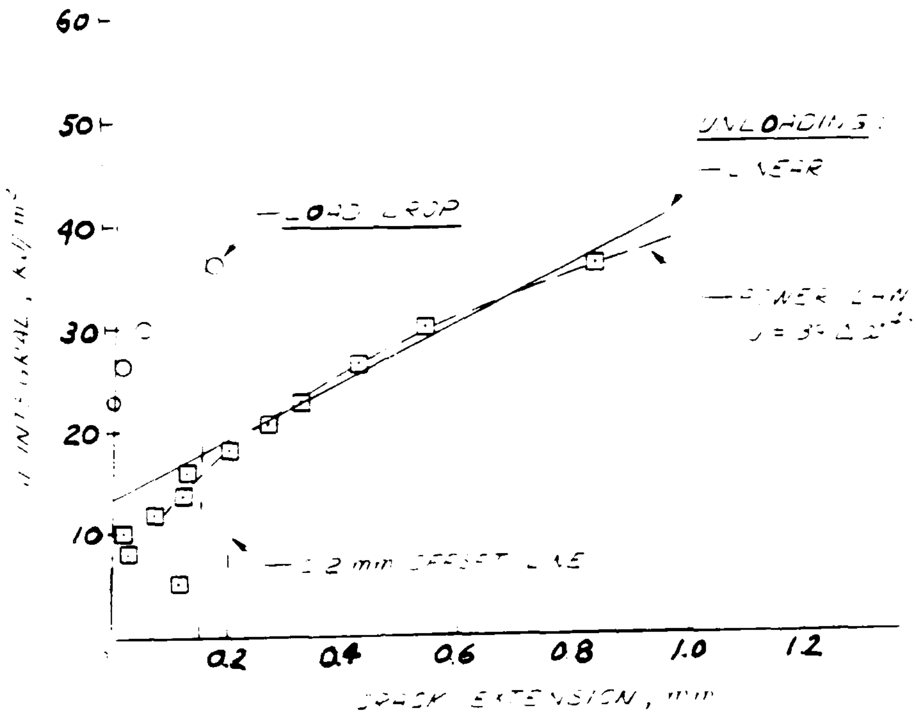

Figure 5. J versus Δa plots for side-grooved specimen 40B, using unloading-compliance and load-drop measurement of Δa.

Load Drop Analysis

Plots of J versus Δa were attempted from the five sets of test results using a load-drop procedure for Δa, where

$$\Delta a = J/2\sigma_y + b_o[1 - (P_{\Delta a}/P_{max})^{1/2}] \qquad (6)$$

In Eq. (6) the first term is the blunting contribution to Δa. The second term is the expression (ref 3) for Δa based on the assumptions that no crack growth

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[3] J. A. Kapp and J. H. Underwood, "Single Specimen J-Based Fracture Toughness Test for High-Strength Steels," Fracture Mechanics: Fourteenth Symposium - Vol. II: Testing and Applications, ASTM STP 791, (J. C. Lewis and G. Sines, eds.), ASTM, 1983, pp. II-402 - II-414.

occurs before maximum load and that all crack growth is described by the bending limit load relation between load and the square of remaining ligament, $P = \text{constant}(b^2)$. Figures 4 and 5 show the type of data obtained. For the nonside-grooved specimens such as in Figure 4, enough data were obtained to perform a linear regression determination of critical J in the same manner as for a J_{Ic} determination. For the side-grooved specimens, as shown in Figure 5, little Δa data were obtained above the 0.15 mm exclusion line.

It is worthy of note that the J versus Δa curve obtained from load-drop analysis has essentially the same slope as that obtained from the unloading-compliance method. In Figure 4, the slope of the load-drop line in the units shown is 0.92, compared with 0.88 for the linear unloading-compliance line. A similar slope from both methods would be expected even if only the second of the two assumptions of the analysis were correct. The first assumption, that no crack growth occurred before maximum load, will be proven wrong by subsequent results here. However, this would affect the position of the curve but not its slope. Therefore, there is some indication that the load-drop method is suitable for determining the tearing modulus of the material tested here.

DISCUSSION OF RESULTS

A summary of key results of the tests and analyses is shown in Table IV. Listed first is the load at which the calibration unloading was performed, relative to maximum load P_{calib}/P_{max}. Using a value of about 0.8 for this ratio and applying the effective modulus procedure of Table II resulted in the bilinear type of J versus Δa curve which is expected, made up of blunting and

TABLE IV. SUMMARY OF TEST RESULTS

Specimen Number	P_{calib}/P_{max}	E^*/E	P_{max}/P_{limit}	$\Delta a_{unload}/\Delta a_{tint}$	J_{Ic} Linear/E813 KJ/m^2	J_c Power Law KJ/m^2	J_c Load-Drop KJ/m^2
40	.77	0.94	0.71	0.46	19.5	28	28.5
47	.86	1.01	0.72	0.47	19.5	28	28.4
40A	.75	0.88	0.60	0.90	8.4	13	-
40B	.79	0.84	0.64	1.04	13.5	18	31†
97	.85	1.01	0.99	0.69	189	285	257

NOTE: J_{Ic} is value at intersection of linear line and blunting line; J_c power law is value at intersection of power law line and 0.2 mm offset line; J_c load-drop is value at intersection of linear line and blunting line.

†Only one of the four Δa values above the 0.15 mm minimum

crack growth portions. The ratio of effective to typical modulus, E^*/E, which was calculated was generally near unity. The side-grooved specimens, 40A and 40B, gave poorer results in this respect than the nonside-grooved specimens. This may be due to the use of effective specimen thickness in the calculations of Table II. The Method E813 calculation of effective thickness was used

$$B_{eff} = B_{gross} - [(B_{gross}-B_{net})^2/B_{gross}] \tag{7}$$

which results in an effective thickness of 4.88 mm for specimens 40A and 40B. It is interesting to note that if $B_{net} = 4.06$ mm were used in the calculations of Table II, the resulting values of E^*/E would be 1.05 and 1.01 for specimens 40A and 40B, respectively. Then all the specimens, side-grooved as well as nonside-grooved, would meet the E813 requirement that, essentially, E must equal E^* within seven percent.

It is generally of interest to compare the maximum load in a J_{Ic} test with the bending limit load. For the tests here this ratio, shown in Table IV, gives an indication of how well the load-drop method would be expected to work. Load-drop would be expected to give a good measure of Δa only for P_{max}/P_{limit} near unity. This was the case for only one of five tests, so based on this, differences between the load-drop and unloading-compliance results would not be unexpected. It should be noted that the work of Server (ref 8), based on plane-strain slip-line-field analysis, was used to obtain the P_{limit} expression for the tests here

$$P_{limit} = 1.435\ \sigma_Y B b^2/S \tag{8}$$

[8] W. L. Server, "General Yielding of Charpy V-Notch and Precracked Charpy Specimens," Journal of Engineering Materials and Technology, Vol. 100, 1978, pp. 183-188.

in which the constant 1.435 was calculated from Reference 8 for an indentor width of 1 mm and for the assumption of the von Mises' yield criterion. The use of a plane-strain analysis for calculating P_{limit} is believed to be appropriate, because the relatively low strain-hardening of the material encourages slip-line type deformation.

Another requirement of Method E813 is that the final measurement of Δa using the unloading-compliance method should agree within 15 percent of that from heat tinting or other crack length marking after the test. Comparison of these two measures of Δa, listed in Table IV, shows that only the side-grooved tests meet the 15 percent requirement. Figure 6 shows the reason. Considerable tunnelling occurred in the nongrooved specimens, whereas relatively straight-fronted crack growth occurred in the side-grooved specimens.

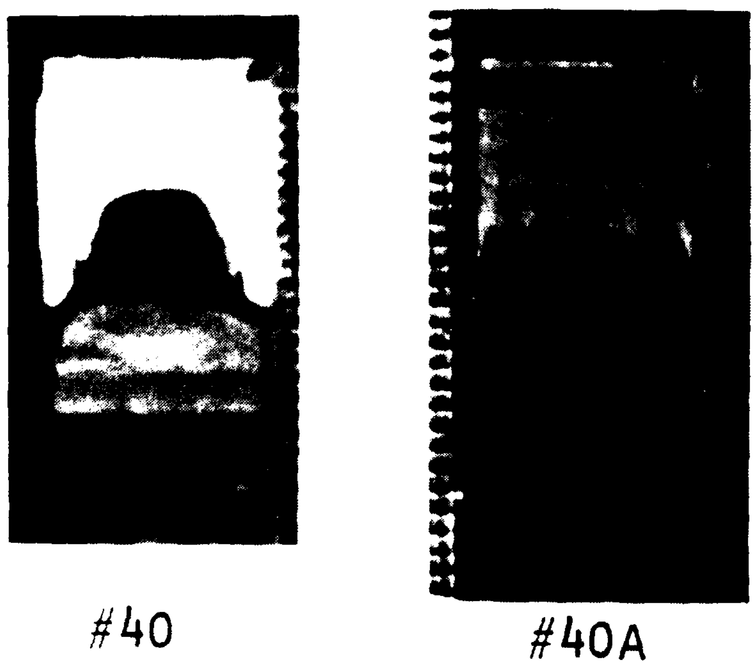

Figure 6. Heat-tinted fracture surfaces of two bend specimens.

The final three columns in Table IV list the critical values of J which were determined using: unloading-compliance and linear regression as in Method E813; unloading-compliance and power law regression; load-drop and linear regression when there were enough data. One consistent trend is that J from the power law method is significantly above obtained that from the linear Method E813, 33 to 55 percent higher. The critical J from the load-drop method is also above that from the linear method, but not as consistently, from 46 to over 200 percent. There is no common reason for these two somewhat similar trends. The power law J is above the linear J because the power law method selects a point higher on the J versus Δa curve for these tests. The load-drop J is above the linear J because the load-drop Δa measurements are significantly below those from unloading-compliance; this shifts the J versus Δa curve upward.

An important trend in the linear J_{Ic} results is a significantly lower J_{Ic} value for side-grooved specimens 40A and 40B, averaging 11 KJ/m^2, compared with nongrooved specimens 40 and 47, averaging 20 KJ/m^2. The lower side-grooved toughness is clearly caused by the much straighter crack front. However, the choice of which value to use in design is not clear. The side-grooved J_{Ic} is a lower bound, but it may be an overly conservative lower bound, because in practice, no geometry similar to a side-grooved specimen is likely to occur and force such an unnaturally straight-fronted crack and associated low toughness. On the other hand, without the knowledge of all possible design and service conditions, there is no guarantee that the lower straight-fronted J_{Ic} value from side-grooved tests is not the appropriate one for a particularly severe set of conditions.

SUMMARY AND CONCLUSIONS

The inclusion of an effective modulus procedure in the unloading-compliance method used with the tests here significantly improved the self-consistency of the results. The use of effective modulus eliminated large variations in the horizontal position of the J versus Δa curve and the associated variations in the J_{Ic} value. The effective modulus procedure may not be necessary under the best of testing conditions, but in general, it should be a required part of the unloading-compliance J_{Ic} test method. For proper general use of effective-modulus, the load-line compliance data in Method E813 should be replaced with more accurate data. The results of Reference 6 are suggested for this purpose. For the tests here, the best results were obtained when calibration unloading and effective modulus procedures were performed at a point approaching maximum load. This is suggested as a general procedure, with care taken to be sure that no crack growth has yet occurred at the calibration unloading point. In general, heat-tinting type tests will be required to positively determine the optimum point for calibration unloading.

The power law regression fit and 0.2 mm blunting line offset approach resulted in critical J values about 40 percent higher than those from the linear fit and blunting line approach of Method E813. For the tests here, a

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[6] J. H. Underwood, J. A. Kapp, and F. I. Baratta, "More on Compliance of the Three-Point Bend Specimen," International Journal of Fracture, Vol. 28, 1985, pp. R41-R45.

0.15 offset would be attractive, because this line is already used for data exclusion and it would result in a closer agreement with results from the current Method E813.

The load-drop procedure resulted in critical J values considerably above those of the unloading-compliance and linear fit approach of Method E813. The primary reason for this is believed to be the occurrence of crack growth before maximum load for this material. Such crack growth would not be indicated by the load-drop method, so the J versus Δa curve would be shifted to the left and a higher critical J value would result. The above serves to emphasize that the load-drop method gives a good measure of J_{Ic} only when it is certain that no crack growth has occurred before maximum load. When this is uncertain, the load-drop critical J value must be considered to be unconservative.

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